Fabrication of Flip-Chip Optical Couplers Between Single-Mode Fibers and LiNbO₃ Channel Waveguides

CATHERINE H. BULMER, SANG K. SHEEM, ROBERT P. MOELLER, AND WILLIAM K. BURNS

Abstract—Highly efficient end-fire optical coupling is described between single-mode fibers and Ti-diffused LiNbO₃ channel waveguides using a Si V-groove/flip-chip configuration. The preparation and alignment of the LiNbO₃ and the Si wafer are discussed. The LiNbO₃ substrate is arranged face down on the Si wafer. The fibers are placed in the Si V-grooves which provide lateral and angular alignment, and approximate vertical alignment, with respect to the channel waveguide. Deep transverse grooves, with tapered fibers lying under the coupling fibers, allow submicron vertical positioning. The fiber ends are prepared by cleaving; the LiNbO₃ channel ends are optically polished.

I. INTRODUCTION

EFFICIENT OPTICAL coupling between single-mode fibers and single-mode Ti-diffused LiNbO₃ channel waveguides is necessary in order to include LiNbO₃ devices in single-mode fiber systems. The coupling should be readily achievable and reproducible. It is difficult to obtain efficient fiber/channel end-fire coupling because of the small dimensions of the guiding regions of the fibers and channel waveguides and because of the mismatch of the aspect ratios of these guides. A single-mode fiber has circular symmetry with a central core, typically 4–6 μm in diameter, and a cladding 70–120 μm in diameter; a single-mode Ti-diffused channel waveguide is formed at the surface of a LiNbO₃ substrate and may be 2–5 μm in width, with a depth of a few micrometers. There are several stringent requirements for fiber/channel waveguide end-fire coupling:

- 1) accurate horizontal, vertical, and angular positioning; we aim to achieve tolerances of $\leq 1 \mu\text{m}$ in translational alignment and $\leq 1^\circ$ in angular alignment (an offset of 1 μm , or an angular tilt of 1° , produces an ~ 10 percent reduction in transmission [1]);
- 2) flat, defect-free waveguide end surfaces, normal to the propagation direction; and,
- 3) for complete coupling, matched field distributions.

Also, to avoid reflection losses, antireflection coatings would be required; the core refractive index of a SiO₂ fiber is ~ 1.46 , whereas LiNbO₃ has an extraordinary refractive index $n_e \cong 2.20$ and an ordinary index $n_o \cong 2.29$ (at 633 nm).

Micromanipulators can be used for precise fiber/channel alignment in end-fire coupling [2]–[4]. Noda and others have

successfully demonstrated such arrangements. However micromanipulators do not allow the formation of a compact rugged coupler; also, simultaneous coupling of fibers at more than one input and output port (channel) is not feasible. Flip-chip coupling was first demonstrated by Hsu *et al.* [5] who end-fire coupled, with up to 47 percent efficiency (corrected for reflection losses) for one mode, between a flipped-over channel waveguide with cleaved ends and an appropriately positioned fiber placed in a V-groove in a Si wafer. Preferentially etched grooves in the Si wafer provide both fiber positioning grooves and alignment (registration) markings for accurate fiber/channel waveguide alignment. Altitudinal alignment in end-fire fiber/fiber coupling using V-grooves was improved by positioning tapered fibers in transverse grooves below the coupling fibers [6]. We consistently measured coupling efficiencies of greater than 70 percent using such tapered alignment fibers in the Si V-groove/flip-chip coupling arrangement shown in Fig. 1, in which the LiNbO₃ substrate rests, face down, on top of a Si wafer with a two dimensional pattern of preferentially etched grooves. We optically polished the LiNbO₃ end faces: this allows arbitrary crystal orientation, independent of the cleavage plane. We used an axial channel propagation direction (X-axis in Z-cut crystal) along which both the transverse electric (TE) (ordinary) and transverse magnetic (TM) (extraordinary) mode propagation losses were low. In earlier flip-chip experiments, the LiNbO₃ ends were always cleaved [5] and extraordinary mode propagation in the channel perpendicular to the cleave was highly lossy. The fiber/channel coupling efficiencies which we measured in several fabricated flip-chip units are in the range 70–88 percent (corrected for reflection losses) and are equal for TE and TM mode polarizations. These efficiencies are only a few percent lower than theoretical coupling estimates for perfect alignment, limited only by mode mismatch, which were determined from scanning the near-field mode distributions. They are as high as measurements made with a micropositioner which allowed exact xyz and angular adjustments and correspond to throughput losses of ≤ 3 dB, from the input fiber, through a 9-mm long channel, to the output fiber, for an arbitrary input optical polarization.

II. FLIP-CHIP CONFIGURATION: MEANS OF ALIGNMENT

In the flip-chip arrangement the LiNbO₃ substrate is flipped over on the Si wafer so that the diffused channel waveguide surface is resting on the Si. Accurate positioning in the horizontal plane is obtained by lining up matching registration

Manuscript received February 13, 1981; revised August 3, 1981. This paper was presented at the 31st Electronic Components Conference, Atlanta, GA, May 11–13, 1981.

C. H. Bulmer, R. P. Moeller, and W. K. Burns are with the Naval Research Laboratory, Washington, DC 20375.

S. K. Sheem was with the Naval Research Laboratory. He is now with Collins Transmission Systems Division, Rockwell International, Dallas, TX 75207.

Fig. 1. Schematic of Si *V*-groove/flip-chip coupling structure.

markings (grooves in Si wafer and channel segments in the LiNbO₃) which are arranged to either side of each coupling fiber *V*-groove in the Si wafer and to either side of each channel waveguide in the LiNbO₃ [5]. The alignment is performed by moving the inverted (flipped-over) LiNbO₃ substrate with respect to the Si wafer, under a microscope with an objective with a long working distance. The registration channels at the LiNbO₃ surface are viewed through the 1-mm LiNbO₃ thickness (the substrate has a see-through polish on its underside). The channels are visible because Ti indiffusion produces a slight swelling of the surface which results in a raised "ridge" along each channel. These ridges are most clearly viewed with a Nomarski (interference-contrast) attachment in the microscope. After alignment, the LiNbO₃ is lightly cemented, at places around its edges, to the Si wafer. Registration lines of 3–8 μm width have been used (typically several lines of various widths). The lines are correctly placed with respect to the grooves or channels to an accuracy of $\sim 0.25 \mu\text{m}$, as determined by the fabrication of the photolithographic masks. The width of the coupling fiber *V*-groove is chosen so that when the fiber sits in the fully etched groove its core is at an appropriate height for coupling to the channel waveguide. Further positioning in the vertical plane is provided by tapered alignment fibers which are placed in deep *V*-grooves, at right angles to the coupling fiber *V*-grooves, so that the tapered fibers lie under the coupling fibers [6] (Fig. 1). These alignment fibers have diameters tapered by 0.5–1 $\mu\text{m}/\text{mm}$ and provide sub-micron altitudinal positioning accuracy. The height of an input or output coupling fiber can be continuously adjusted by pushing or pulling the tapered fiber, at input or output, in its transverse groove so that the output power is maximized. A smoothly tapered alignment fiber is formed by etching in a buffered HF solution, while slowly withdrawing the fiber from the solution with a motor drive. The use of tapered fibers for fine altitudinal alignment allows some tolerance in the coupling fiber *V*-groove depths and in the coupling fiber parameters. Otherwise a high coupling efficiency could be realized only with *V*-grooves precisely etched to the depth appropriate for a coupling fiber with a precisely known core position, i.e., a fiber of known outer diameter and perfect core/cladding concentricity.

III. SI WAFER *V*-GROOVE DEFINITION

We used 1-mm thick, 2-in diameter (100) Si wafers of $\sim 2000 \Omega\text{-cm}$ resistivity. An $\sim 1\text{-}\mu\text{m}$ thick masking layer of SiO₂ was thermally grown. We aligned the photolithographic groove mask with the manufacturer's flat cut along the [110] direction. The complete groove pattern was defined over all the Si wafer and the SiO₂ masking layer was etched using a buffered HF solution. However, at either end of the central region where the LiNbO₃ is placed, we etched only part way through the SiO₂ layer so that the registration lines were formed only in the SiO₂ and were not overetched during the Si *V*-groove etching. If this were not done, overetching of the narrow registration lines occurred: there was 1 μm or more undercutting, depending on how well the mask was aligned with respect to the Si wafer. Therefore, after etching $\sim 0.2 \mu\text{m}$ of the SiO₂ layer, we used a second mask with two rectangular openings to define a photoresist pattern which protected the desired regions. The remainder of the SiO₂ was then etched. The wide coupling and alignment fiber grooves (up to 190- μm wide) were fully etched in the Si using a potassium hydroxide/isopropanol/water mixture or an ethylenediamine/pyrocatechol/water mixture [7]. The former solution was typically used. It results in less undercutting of the Si (having a greater (100)/(111) differential etch rate) but has a much smaller Si/SiO₂ differential etch rate than the latter solution. Provided that a sufficiently thick SiO₂ layer, $\sim 1 \mu\text{m}$, was used, the relatively fast KOH etching of the SiO₂ caused no problem. Very wide grooves were also etched in the Si in any regions which would be adjacent to metal electrodes or electrode leads on the LiNbO₃ surface in the flip-chip arrangement. This is necessary to prevent capacitive coupling between the Si and any electro-optic device which was formed in the LiNbO₃. The complete pattern in the Si wafer consisted of many coupling grooves, with varying depths, appropriate for different fiber diameters, and deeper transverse alignment grooves to either side of the substrate region. Coupling in turn to each of many different channel waveguides and waveguide devices is therefore possible with a single unit. Typically we have coupled sequentially to six waveguides in the same unit.

IV. WAVEGUIDE END PREPARATION: OPTICAL POLISHING OF LiNbO₃ CHANNEL ENDS

We used only cubic LiNbO₃ waveguide orientations in order to avoid anisotropic leaky mode [8] and double-refraction effects [9], [5]. These effects occur when modes are propagated along a nonaxial direction and result in polarization-dependent propagation losses and coupling efficiencies. As LiNbO₃ has only one cleavage plane along a nonaxial direction, coupling to a cleaved-end waveguide, and propagation along the waveguide, can be optimized for only one polarization. The cubic end faces of the LiNbO₃ were therefore prepared by polishing. The substrate ends should be very flat, with no chips and minimal rounding. We first used an optical contact polishing technique. The Ti-diffused LiNbO₃ substrate was optically contacted to a dummy LiNbO₃ substrate and the back faces were cemented to large glass blocks for ease of handling. The input and output edges were ground and then

polished in turn and the substrates were then separated by gentle heating. To allow optical contact, Ti was indiffused over the entire LiNbO_3 surface except close to the channel pattern; the slight surface swelling due to indiffusion therefore occurred over almost all the surface. There is no gap between the substrates and excellent chip-free edges with no observable rounding and no fracture lines were obtained. The photograph in Fig. 2 shows a diffused channel waveguide, terminating in an optically polished end. However, optical contact can be used only if the substrate is flat to $\sim\lambda/2$. During diffusion some substrates lost flatness. When substrates of greater thickness (2, 3, or 4 mm instead of 1 mm) were used, little change in flatness occurred during diffusion, but accurate photolithographic processing was more difficult. Also 1-mm thick substrates which had previously been annealed showed less change in flatness. However even with very flat diffused substrates, optical contact was occasionally lost during the polishing process. Later substrates were therefore prepared using a very thin layer of optical cement¹ between the diffused substrate and the dummy, or between two diffused substrates (no dummy). Using this method we have simultaneously polished eight substrates in one glass block unit. The stringent substrate flatness requirement was thus avoided and the cemented substrates never separated during the blocking or polishing procedures. After polishing each edge, we removed the cement by heating in a decementing agent.¹ Care was needed to avoid chipping as the two substrates were separated. Again very good quality edges were consistently obtained.

Very flat fiber ends, normal to the fiber axis and with little or no lip, were prepared by conventional cleaving. If the fiber and channel waveguide field distributions are perfectly matched, 100 percent coupling is possible (neglecting reflection losses which can be minimized with antireflection coatings). Perfect matching is not possible, however, because the channel waveguide field distribution has a nonunity aspect ratio (it is approximately rectangular with greater width, parallel to the surface, than depth, perpendicular to the surface), is asymmetric perpendicular to the surface, and is not exactly Gaussian either parallel or perpendicular to the surface. In contrast, the fiber field is circularly symmetric and is essentially Gaussian [10], [5]. The channel waveguide field aspect ratio can be optimized somewhat by appropriate choice of Ti-diffusion conditions [11], [4] but the asymmetry perpendicular to the surface, due to there being air above the waveguide and undiffused LiNbO_3 with a much higher refractive index below it, will still exist. One approach to eliminating this asymmetry might be to bury the diffused waveguide beneath the surface with undiffused LiNbO_3 all around it. With a channel waveguide at the LiNbO_3 surface there must always be some coupling loss due to the asymmetry of the field distribution perpendicular to the surface and the resultant field mismatch.

V. LiNbO_3 SUBSTRATE AND FIBER PREPARATION

For measurements at 633 nm with a HeNe laser, we defined 3- or 4- μm wide straight channel waveguides and Mach-Zehnder waveguide interferometers [12] in 170–220 Å Ti on

Fig. 2. Photograph of LiNbO_3 polished edge, showing 3- μm wide Ti-diffused channel waveguide with "broken" registration channels to either side and planar Ti-diffused regions beyond.

Z-cut X-propagating LiNbO_3 substrates. The diffusion was performed at 1000°C, for 6 h, in O_2 and, in some cases, in the presence of stoichiometric LiNbO_3 powder to inhibit Li_2O out-diffusion (out-diffusion results in a very small increase in extraordinary refractive index at the LiNbO_3 surface; the ordinary refractive index is not affected) [13], [14]. The channel mask had been aligned with respect to the LiNbO_3 substrate edges, using lines in the mask, so that the channels were perpendicular, to $\sim 1^\circ$, to the edges which were then polished. A SiO_2 buffer layer was deposited on each substrate to isolate the optical waveguides from the 1500 Å thick Al electrodes which were later defined along the straight channels to form phase-shifters [15] or around the interferometers to form modulators [12], [16]. We used ITT single-mode fused-silica fiber with numerical aperture (NA) ~ 0.1 and core and cladding diameters of 4.5 and 88 μm , respectively. The offset between the core and cladding centers was specified as $\leq \pm 0.4 \mu\text{m}$. The outer plastic jacket was removed in the coupling region and along sections of the input and output fibers where cladding modes were stripped with a black high-index liquid. The fiber beat length was ~ 20 m. Measurements were made separately for each optical polarization. The polarization was rotated with a half-wave plate at the input to the ~ 0.5 -m long input fiber and it was checked at the fiber output. The polarization was maintained to ~ 99 percent or better. In some measurements at 830 nm, using a GaAlAs laser, another ITT single-mode fiber with a much shorter beat length and a 78- μm cladding diameter was used. A single polarization, maintained to 99 percent or better, could still be obtained at the end of the input fiber by rotating the input fiber until the light was launched along the appropriate fiber axis for polarization maintenance. Measurements at 830 nm required Ti thicknesses of ~ 300 Å, diffused for 6 h in the LiNbO_3 .

VI. COUPLING MEASUREMENTS

Before using Si wafers, measurements were made with a fiber in an xyz micropositioner with two angular adjustments. The fiber was coupled to a 9-mm long channel on LiNbO_3 sample number 6/2 and a lens was used to focus the channel

¹ Lens bond optical cement, type M-62, and decementing agent from Summers Laboratories, Inc., Fort Washington, PA 19034.

output through a pinhole on to the detector. Light which had been coupled into the substrate, not the channel, was screened off. Correcting for reflection losses, 77 and 72 percent throughputs were obtained for the 3- and 4- μm wide channels, respectively, for both TE and TM mode polarizations. Loss occurs in input coupling and in channel mode propagation. Again using the micropositioner, the output coupling efficiency from channel to fiber was measured as 76 percent, i.e., of the same order as the input coupling plus channel transmission. Then if we assume equal input and output coupling, this result indicates that both TE and TM channel mode attenuations were very small and were of the order of the experimental error of ± 5 percent or ≤ 0.5 dB/cm. Any mode attenuation along the 9-mm long channels was entirely neglected in subsequent flip-chip coupling efficiency calculations. The same input fiber was next placed in a Si wafer in the flip-chip arrangement described, and 76 and 72 percent coupling (throughput) obtained from the fiber to each of the 3- and 4- μm wide channels, respectively, for each mode polarization. Thus the flip-chip coupling efficiencies are as high as those obtained with a micropositioner and are independent of the input optical polarization. For each channel, the coupling for one mode polarization was optimized with the fiber in the same position as for the other mode polarization. With input and output fibers aligned to the 3- μm channel in the flip-chip unit, we obtained 52 percent (TE mode) and 51 percent (TM mode) actual throughputs with water ($n = 1.33$) as index-matching liquid. These correspond to average input/output (fiber to channel/channel to fiber) coupling efficiencies, not corrected for reflected losses, of 72 percent (TE) and 71 percent (TM).

We have measured fiber/channel coupling efficiencies of 70–88 percent, corrected for reflection losses, for TE and TM modes, as shown in Table I. These correspond to an average coupling efficiency of 80 percent or 1 dB loss. We used 3- and 4- μm wide channels on each of five LiNbO_3 substrates cemented to Si wafers and fiber/channel separations of < 10 μm (theoretically, a 10- μm separation causes a 10 percent reduction in coupling compared to a zero separation). Within a few percent, the same values were always obtained for coupling with TE or TM modes in a particular channel and optimum coupling with each mode was obtained with the fiber in the same position. Measurements were repeatable within ~ 10 percent provided that the Si and LiNbO_3 were accurately aligned, to ~ 1 μm . The same coupling efficiencies were determined for coupling with one input fiber and a lens at the output, or with input and output fibers. The transmission could be smoothly varied between maximum and near zero by moving the tapered alignment fiber. If the coupling fiber V-grooves were a few μm too deep for a particular fiber, we found that the coupling fiber could be moved horizontally as well as vertically (because of friction between the coupling and alignment fibers) which improved transmission if the Si/ LiNbO_3 transverse alignment was imperfect. Small Fabry-Perot resonances were sometimes observed, in the air gap between fiber and channel or in the channel itself [16]. These occur when the guide end faces are exactly flat, parallel, and normal to the propagation direction. Even in substrates (numbers 6/2, 7/2, 9/2) where a planar out-diffused mode (extraordinary polarization only, i.e., TM) could propagate, efficient coupling was still obtained

TABLE I
MEASURED FIBER/CHANNEL WAVEGUIDE FLIP-CHIP
COUPLING EFFICIENCIES¹

LiNbO ₃ Substrate	Ti Thickness (Å)	Coupling Efficiency (percent)			
		3- μm channel		4- μm channel	
		TE	TM	TE	TM
6/2	170	76	76	72	72
7/2	175	84	85	79	83
7/3	175	86	85	85	87
9/2	180	85	88	82	83
9/5	220	73	70	70	74

¹ At $\lambda = 633$ nm (corrected for reflection losses; air between fibers and channels).

between the fiber and the indiffused channel mode. Negligible power was coupled from the fiber to the out-diffused mode, as seen from the fact that coupling efficiencies from the fiber to TE and TM modes were equal and there are no ordinary (TE) out-diffused modes. A planar out-diffused mode, guided in a relatively deep surface layer with only a slight refractive index change, has a very different field distribution from an indiffused channel mode, which is confined in a three-dimensional surface layer, an order of magnitude shallower, but with an order of magnitude greater refractive index change. The fiber mode is closely matched with only the indiffused channel mode.

VII. MODE FIELD DISTRIBUTION MEASUREMENTS AND CALCULATIONS OF MAXIMUM POSSIBLE COUPLING

For comparison we determined the maximum coupling efficiency, for perfect alignment and zero separation limited only by the mode field mismatch. Mode intensity distributions were plotted by scanning a 100- μm diameter pinhole through the maximum intensity point in the horizontal (x) and vertical (y) directions across the magnified near-field images of the channel waveguide and fiber outputs. A $\times 63$ microscope objective, positioned a few millimeters from the guide end face, produced an image magnified 550 times. The mode profiles were smooth, as can be seen in Fig. 3, and showed no indication of imperfections in the end surfaces. By measuring the distance between the $1/e$ points of the intensity profiles and the magnification of the projection system, we determined the Gaussian mode field half-widths, which are shown in Table II for substrate number 7/3. A Gaussian electric field distribution in, for instance, the x direction can be represented as $E_x \propto \exp(-x^2/w_x^2)$. Then the spacing of the $1/e$ points of the E_x^2 intensity profile is equal to $\sqrt{2}w_x$. The half-widths of the channel field are w_x and w_y , of the rectangular Gaussian [10] which approximates the waveguide mode electric field (w_x parallel and w_y perpendicular to the surface). The fiber, with a circular Gaussian field, produced identical scans in the x and y directions with a field half-width, or mode radius, of $a = 3.0$ μm . For perfect alignment, zero separation, and no reflection losses, the power coupling coefficient is [10]

$$\kappa_m = 0.93 \frac{4}{\left(\frac{w_x}{a} + \frac{a}{w_x}\right) \left(\frac{w_y}{a} + \frac{a}{w_y}\right)} \quad (1)$$

Fig. 3. Measured near-field intensity distributions, scanned in y direction, of fiber and $3\text{-}\mu\text{m}$ wide channel (substrate number 7/3), for TE mode polarization. Distance scale is shown in terms of actual mode size. Scanned image was magnified 550 times. Intensity is in arbitrary units; the maximum intensity point was selected as $y = 0$.

TABLE II
MEASURED CHANNEL MODE FIELD HALF-WIDTHS w_x, w_y
AND CORRESPONDING THEORETICAL MAXIMUM
COUPLING EFFICIENCIES κ_m AND κ_m' ¹

Mode		w_x (μm)	w_y (μm)	κ_m (percent)	κ_m' (percent)
3- μm channel	TE	2.9	2.2	88	92
	TM	3.6	3.0	91	93
4- μm channel	TE	2.9	2.0	86	89
	TM	3.2	2.3	89	92

¹ w_x, w_y (substrate number 7/3), κ_m from (1) and κ_m' from (2) ($\lambda = 633\text{ nm}$).

where 0.93 is a correction for the deviation of the real mode fields from their Gaussian approximations. The κ_m values determined from the measured mode widths are shown in Table II. The experimental coupling efficiencies are a few percent lower. Maximum coupling efficiencies were also estimated by numerically overlapping the normalized mode profiles along the x and y directions to give the power coupling coefficient:

$$\kappa_m' = \frac{\int E_{1x}E_{2x} dx \int E_{1y}E_{2y} dy}{\left[\int E_{1x}^2 dx \int E_{1y}^2 dy \int E_{2x}^2 dx \int E_{2y}^2 dy \right]^{1/2}} \quad (2)$$

where each integral is evaluated across the entire mode distribution (from $-\infty$ to $+\infty$) and the subscript 1 refers to the

fiber field (E_{1x} and E_{1y} identical) and 2 refers to the channel field. The κ_m' values are shown in Table II. They are 2–4 percent higher than the κ_m values, which indicates that for these fields the correction factor 0.93 in (1) is slightly conservative. The high magnitudes of the maximum coupling efficiencies (average value of κ_m' is 92 percent or -0.4 dB) indicate that the fiber/channel mode match is good.

VIII. FLIP-CHIP COUPLED VOLTAGE-CONTROLLED LiNbO_3 DEVICES

As the fiber/channel coupling is highly efficient, it is feasible to include LiNbO_3 devices in fiber systems to, for instance, phase-shift, modulate, or switch the light in a fiber. Polarization-independent electro-optic modulators [12], [16] and phase shifters [15] have been formed in LiNbO_3 and successfully operated in flip-chip units. When efficient coupling has been achieved by moving the alignment fibers, as described, in the flip-chip configuration, the coupling fibers can be secured with a very small amount of adhesive² placed at each fiber/channel interface. The adhesive is cured by exposure to ultraviolet (UV) light. The alignment fibers and all fiber support stages can then be removed without affecting the coupling. With the addition of adhesive, the only change in transmission is due to decreased reflection losses (~ 3.5 percent reflectivity at each fiber/channel interface with adhesive compared to ~ 18 percent with air) and the coupling efficiencies, corrected for reflection losses, are unchanged. In the flip-chip coupled phase-shifter shown in Fig. 4, the fibers are cemented to the channel waveguide ends. When the device was rotated at fast rates in a fiber gyroscope, the coupling remained constant. Thus, with the fibers cemented, a stable, compact, efficient coupling unit is obtained. With care several fibers might be pigtailed to one LiNbO_3 substrate.

Polarization-independent device behavior, i.e., identical and simultaneous processing of both polarization states, is needed for the LiNbO_3 to be fully compatible with the circular cross-section input and output fibers which can support an arbitrary polarization and can excite both TE and TM modes in the LiNbO_3 . Metal electrodes were defined on the SiO_2 buffer layer. We used horizontal and vertical field electrode configurations [12] with gapwidths of $\sim 4\text{ }\mu\text{m}$. The electrodes provide approximately independent control of the horizontal and vertical electric field components, allowing independent control of the TE and TM modes. Provided that grooves had been etched in the Si wafer in the proximity of the electrodes and electrode leads, the phase-shifter, or modulator, response to applied voltages was the same if it were operated in the flip-chip unit, or with no Si wafer (and micro-positioners holding the input and output fibers). The device capacitance was increased by the long electrode leads which extended along the LiNbO_3 surface to beyond the edges of the Si where $25\text{-}\mu\text{m}$ diameter gold wires were bonded for external voltage connections. The phase-shifter or modulator operation was found to be identical for dc or ac voltages applied to the electrodes provided that a good quality SiO_2 buffer

² Optical adhesive NOA-61 from Norland Products, Inc., North Brunswick, NJ 08902.

Fig. 4. Photograph of fiber-coupled LiNbO₃ channel waveguide phase-shifter. LiNbO₃ is cemented to Si wafer and fibers are attached with optical adhesive to the channel waveguide ends. Alignment fibers were removed after the adhesive was cured.

layer had been formed, with approximately infinite resistance between the electrodes. Measurements have also been made at 830 nm with fiber-coupled channels and modulators. The coupling efficiencies are similar to those measured at 633 nm.

IX. CONCLUSION

We have fabricated Si *V*-groove/flip-chip units for highly efficient optical coupling between single-mode fibers and Ti-diffused LiNbO₃ channel waveguides. The preparation and alignment of the Si wafer and the LiNbO₃ substrate have been discussed. The LiNbO₃ is positioned face down on the Si wafer by aligning registration channels, on either side of the channel to be coupled, with matching registration markings on the Si wafer. The coupling fibers are positioned in preferentially etched Si *V*-grooves and their height is finely adjusted by means of tapered alignment fibers pushed underneath, in deep transverse *V*-grooves. The LiNbO₃ channel ends are optically polished and the propagation direction is along a major LiNbO₃ axis. We have achieved both fiber/channel coupling efficiencies and channel mode propagation losses which are independent of the input optical polarization. Coupling between a fiber and either a TE or TM channel mode was optimized for the same fiber position. The TE and TM channel mode attenuations are ≤ 0.5 dB/cm. The fiber/channel coupling efficiencies of 70–88 percent are as high as measurements made with a micropositioner, instead of the Si *V*-grooves, and only a few percent lower than theoretical estimates of

maximum coupling limited only by the mismatch of the measured channel and fiber mode profiles. The same high coupling efficiencies are also obtained when the fibers are cemented to the channel waveguide ends after alignment in the flip-chip configuration. Stable compact coupling units are thus obtained.

ACKNOWLEDGMENT

We should like to thank J. P. Gunn for polishing the LiNbO₃ edges, J. F. Bass and G. V. Hodge for performing the LiNbO₃ photolithography, and E. J. West for metal depositions. We are also grateful to C. Nelson for information concerning the optical cement used in LiNbO₃ polishing.

REFERENCES

- [1] D. Marcuse, "Loss analysis of single-mode fiber splices," *Bell Syst. Tech. J.*, vol. 56, pp. 703–718, May–June 1977.
- [2] J. Noda, O. Mikami, M. Minakata, and M. Fukuma, "Single-mode optical-waveguide fiber coupler," *Appl. Optics*, vol. 17, pp. 2092–2096, July 1978.
- [3] R. Keil and F. Auracher, "Coupling of single-mode Ti-diffused LiNbO₃ waveguides to single-mode fibers," *Optics Comm.*, vol. 30, pp. 23–28, July 1979.
- [4] M. Fukuma and J. Noda, "Optical properties of titanium-diffused LiNbO₃ strip waveguides and their coupling-to-a-fiber characteristics," *Appl. Optics*, vol. 19, pp. 591–597, Feb. 1980.
- [5] H. P. Hsu, A. F. Milton, and W. K. Burns, "Multiple fiber end fire coupling with single-mode channel waveguides," *Appl. Phys. Lett.*, vol. 33, pp. 603–605, Oct. 1978.
- [6] S. K. Sheem and T. G. Giallorenzi, "Two-dimensional silicon grooves for altitudinal alignment in fiber end-butt coupling," *Optics Lett.*, vol. 3, pp. 73–75, Sept. 1978.
- [7] K. E. Bean, "Anisotropic etching of silicon," *IEEE Trans. Electron. Devices*, vol. ED-25, pp. 1185–1193, Oct. 1978.
- [8] S. K. Sheem, W. K. Burns, and A. F. Milton, "Leaky-mode propagation in Ti-diffused LiNbO₃ and LiTaO₃ waveguides," *Optics Lett.*, vol. 3, pp. 76–78, Sept. 1978.
- [9] I. P. Kaminow and L. W. Stulz, "Loss in cleaved Ti-diffused LiNbO₃ waveguides," *Appl. Phys. Lett.*, vol. 33, pp. 62–64, July 1978.
- [10] W. K. Burns and G. B. Hocker, "End fire coupling between optical fibers and diffused channel waveguides," *Appl. Optics*, vol. 16, pp. 2048–2050, Aug. 1977.
- [11] M. Fukuma, J. Noda, and H. Iwasaki, "Optical properties in titanium-diffused LiNbO₃ strip waveguides," *J. Appl. Phys.*, vol. 49, pp. 3693–3698, July 1978.
- [12] W. K. Burns, T. G. Giallorenzi, R. P. Moeller, and E. J. West, "Interferometric waveguide modulator with polarization-independent operation," *Appl. Phys. Lett.*, vol. 33, pp. 944–947, Dec. 1978.
- [13] J. R. Carruthers, I. P. Kaminow, and L. W. Stulz, "Diffusion kinetics and optical waveguiding properties of outdiffused layers in lithium niobate and lithium tantalate," *Appl. Optics*, vol. 13, pp. 2333–2342, Oct. 1974.
- [14] W. K. Burns, C. H. Bulmer, and E. J. West, "Application of Li₂O compensation techniques to Ti-diffused LiNbO₃ planar and channel waveguides," *Appl. Phys. Lett.*, vol. 33, pp. 70–72, July 1978.
- [15] C. H. Bulmer and R. P. Moeller, "Fiber gyroscope with non-reciprocally operated, fiber-coupled LiNbO₃ phase shifter," *Optics Lett.*, vol. 6, Nov. 1981.
- [16] C. H. Bulmer, S. K. Sheem, R. P. Moeller, and W. K. Burns, "High-efficiency flip-chip coupling between single-mode fibers and LiNbO₃ channel waveguides," *Appl. Phys. Lett.*, vol. 37, pp. 351–353, Aug. 1980.